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Total ownership cost reduction case study : AEGIS radar phase shifters

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NAVAL POSTGRADUATE SCHOOL

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MBA PROFESSIONAL REPORT

Total Ownership Cost Reduction Case Study: AEGIS Radar Phase Shifters

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December 2006

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13. ABSTRACT *(maximum 200 words)*

The goal of this research is to provide a case study that captures the production and design processes and program management solutions used to reduce total ownership costs of AEGIS Radar Phase Shifters. Specifically, it will focus on the design and redesign of the SPY-1 radar phase shifter; a redesign that dramatically improved performance without increasing Average Procurement Unit Costs (APUC). The researchers will analyze various process- improvement projects (PIP) used to reduce touch-labor and improve production process yield (percentage of manufactured items that are defect-free) of SPY-1B/D phase shifters, and will review programs that improved phase shifter production either directly or indirectly, i.e., consolidated purchasing, lean and six sigma, productivity improvement projects, etc. This case study was conducted with the sponsorship and assistance of the Acquisition Research Program, Graduate School of Business & Public Policy, Naval Postgraduate School, Monterey, CA.

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TOTAL OWNERSHIP COST REDUCTION CASE STUDY: AEGIS RADAR PHASE SHIFTERS

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Submitted in partial fulfillment of the
requirements for the degree of

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TOTAL OWNERSHIP COST REDUCTION CASE STUDY: AEGIS RADAR PHASE SHIFTERS

ABSTACT

The goal of this research is to provide a case study that captures the production and design processes and program management solutions used to reduce total ownership costs of AEGIS Radar Phase Shifters. Specifically, it will focus on the design and redesign of the SPY-1 radar phase shifter; a redesign that dramatically improved performance without increasing Average Procurement Unit Costs (APUC). The researchers will analyze various process-improvement projects (PIP) used to reduce touch-labor and improve production process yield (percentage of manufactured items that are defect-free) of SPY-1B/D phase shifters, and will review programs that improved phase shifter production either directly or indirectly, i.e., consolidated purchasing, lean and six sigma, productivity improvement projects, etc. This case study was conducted with the sponsorship and assistance of the Acquisition Research Program, Graduate School of Business and Public Policy, Naval Postgraduate School, Monterey, CA.

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I. INTRODUCTION

A. AEGIS BACKGROUND

AEGIS (named after the mythological armor shield of Zeus), is the Navy's most capable surface-launched missile system ever put to sea. State-of-the-art radar, missile-launching systems, computer programs, and displays are fully integrated to work in concert to detect incoming missile or aircraft threats, sort them by assigning a threat value, assign on-board Standard surface-to-air missiles, and guide them to their targets. This makes the AEGIS system the first fully integrated combat system capable of simultaneous warfare against air, surface, subsurface and strike threats. Anti-air warfare elements include the Radar System AN/SPY-1, Command and Decision System, and Weapons Control System. AEGIS can track up to 100 targets at any time (Figure 1).

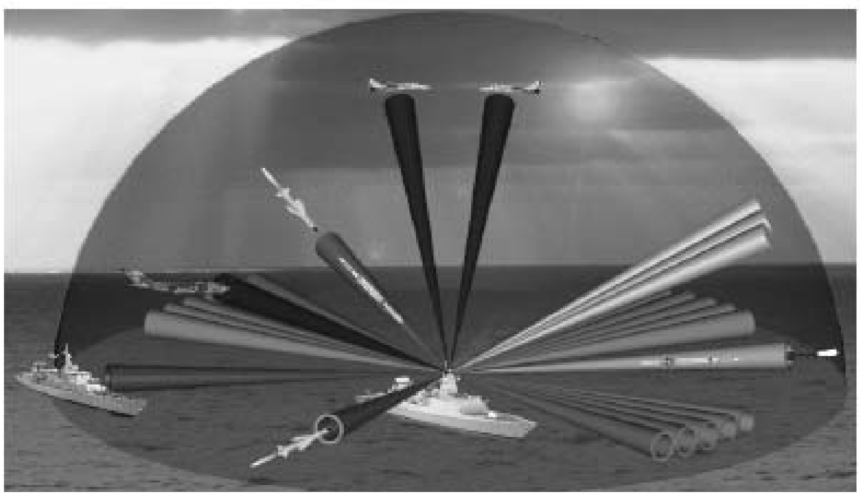

Figure 1. Radar Panels
Note: The radar panels are flat structures, mounted to give the ship 360-degrees of coverage.
(Source: From Van Genderen, undated)

For many years, the US Navy has developed systems to protect itself from attacks. Since the end of World War II, several generations of anti-ship missiles have emerged as threats. The threat posed by such weapons was confirmed in April 1988, when two Iranian surface combatants fired on US Navy ships in the Persian Gulf. The resulting exchange of anti-ship missiles led to the destruction of an Iranian frigate and

corvette by US-built Harpoon missiles. Modern anti-ship missiles can be launched from several hundred miles away, and the attacks can be coordinated—combining air, surface and subsurface launches so missiles arrive on-target almost simultaneously.

The US Navy's defense against this threat has continued to rely on the winning strategy of defense-in-depth. Guns on Navy ships were replaced in the late fifties by the first generation of guided missiles. By the late sixties, these missiles continued to perform well, but the DoD recognized that reaction time, firepower, and operational availability in all environments did not measure up to the potential threat. To counter this, an operational requirement for an Advanced Surface Missile System (ASMS) was promulgated, and a comprehensive engineering development program was initiated to meet that requirement. ASMS was re-named AEGIS in December 1969 (Jane's.com, 2006). In 1974, the USS NORTON SOUND (AVM 1) was fitted with the AEGIS Engineering Development Model (EDM-1), including one SPY-1 Phased-array Radar. The power and effectiveness of AEGIS was demonstrated on May 17, 1974, when the AEGIS Weapon System, manned by the crew of NORTON SOUND, successfully detected, tracked, engaged, and intercepted a BQM-34A Target on the Pacific Missile Test Range with the first firing of the Standard-1 Missile. Later, a second non-warhead Standard-1 Missile was fired and physically intercepted and destroyed the target at a range of 15 miles. Rear Admiral Wayne E. Meyer, AEGIS/SM-2/AEGIS Ship Acquisition Manager (considered "Father of AEGIS") termed this performance "A 7 league advance in our Navy's ability to go once more in harms way" (USS NORTON SOUND, 2006).

After success with the EDM-1 shipboard application, the decision was made to construct the first AEGIS ships based on the hull and machinery designs of Spruance class destroyers. The sophistication and complexity of the AEGIS combat system were such that the combination of engineering with AEGIS ship acquisition demanded “special management treatment.” This combination was affected by the establishment of the AEGIS shipbuilding project at the Naval Sea Systems Command (NAVSEA PMS-400) in 1977 (Jane's.com, 2006). The special management treatment combined the structured hull mechanical and electrical systems, combat systems, computer programs, repair parts,

personnel maintenance documentation, and tactical operation documentation into one unified organization to create the highly capable, multi-mission surface combatants that are today's AEGIS cruisers and destroyers. The charter for NAVSEA PMS-400 represented a significant Navy management decision, one which had far-reaching impacts on acquisition management, design, and lifecycle support of modern Navy ships. For the first time in the history of surface combatants, PMS-400 introduced an organization that had both responsibility and authority to simultaneously manage development, acquisition, systems integration, and lifecycle support.

Originally identified as a guided missile destroyer, the DDG-47 class was re-designated a guided missile cruiser. The first ship of the class, USS TICONDEROGA CG-47, was commissioned on January 23, 1983. CG-52 opened a new era in surface warfare as the first AEGIS ship with the Vertical Launching System (VLS), allowing greater missile selection, firepower and survivability. The improved AN/SPY-1B radar went to sea in CG-59 through CG-73, ushering in another advance in AEGIS capabilities.

Advances in technology throughout the 1980s made it possible to build an AEGIS system with a smaller ship while maintaining multi-mission capabilities. The smaller ship was designed using an improved sea-keeping hull form, reduced infra-red and radar cross-section and upgrades to the AEGIS Combat System such as the SPY-1D. The first ship of the DDG-51 class, USS ARLEIGH BURKE, was commissioned on July 4, 1991. The DDG-51 class was named after a living person, the legendary ADM Arleigh Burke, the most famous destroyerman of World War II (Jane's.com, 2006). DDG-51s were constructed in flights, allowing technological advances during construction. Flight II, introduced in FY1992, incorporated improvements to the SPY radar and the Standard missile, active electronic countermeasures, and communications. Flight IIA (Figure 2), introduced in FY1994, added a helicopter hangar with one anti-submarine helicopter and one armed attack helicopter.

Figure 2. USS OSCAR AUSTIN (DDG 79).
Note: This is the First Flight IIA, commissioned August 2000
(Source: From Global Security.org, 2006)

Although DDG-51s were constructed in flights, the combat systems are upgraded in baselines. The baselines are described as follows:

- Baseline 2: Vertical Launching System, Tomahawk Weapon System, and Anti-submarine Warfare upgrades.
- Baseline 3: AN/SPY-1B radar and AN/UYQ-21 consoles.
- Baseline 4: Integration of AN/SPY-1D radar and AN/UYK-43/44 computers with superset computer programs developed for DDG-51 class.
- Baseline 5: Joint Tactical Information Distribution System, Command and Control Processor, Tactical Data Information Link 16 and Information Exchange System, and AEGIS Extended-range Missile.
- Baseline 6: First combat systems operating system run via local area networks that integrate AEGIS legacy equipment with commercial-off-the-shelf (COTS) technology. COTS technology actually controls all primary processors instead of only using COTS for backup/secondary processing.
- Baseline 7: Latest AEGIS upgrade (September 2005) includes a new radar, AN/SPY-1D(V), which has enhanced electronic countermeasures and increased capability in littoral environments. Baseline 7 is based on COTS computer architecture (Naval-Technology.com, 2006).

To date, AEGIS Weapon System capabilities have been installed on 76 US Navy cruisers and destroyers. Plans are currently underway to install the system on an additional 13 Destroyers. The SPY-1D(V) littoral radar upgrade superseded the SPY-1D in new-construction ships beginning in FY 1998 and first deployed in 2005. AEGIS is the primary naval weapon system for Japan, and is part of two European ship construction programs—the Spanish F-100 and the Norwegian New Frigate. Additionally, Australia and the Republic of Korea recently selected AEGIS for its newest platforms (Lockheed Martin, 2006).

B. PRINCIPLES OF PHASED-ARRAY RADAR ANTENNAS

Electronically scanned antennas have broad applicability for both commercial and military applications, including advanced military radars, cellular base stations, satellite communications, and automotive anti-collision radar. There are many benefits to electronically scanned antennas, including fast scanning, the ability to host multiple antenna beams on the same array, and the elimination of mechanical complexity and reliability issues. Because phased-array radar antennas require no physical movement (Figure 3), the beam can scan at thousands of degrees per second, fast enough to irradiate and track many individual targets and still run a wide-ranging search periodicity.

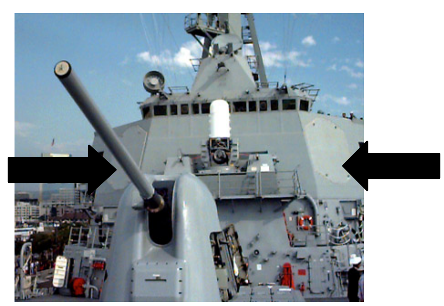

Figure 3. Spy-1D Phased-array Radar Antennas (2 of 4 shown)
(Source: After Global Security.org, 2006)

A SPY-1 Phased-array Radar Antenna consists of 4500 elements that are essentially miniature individual antennas. These elements are arrayed in patterns depending on the desired performance characteristics needed by the application, such as operating frequencies, antenna gain, sensitivity, and power requirements. Each of these elements requires a phase shifter (Figure 4).

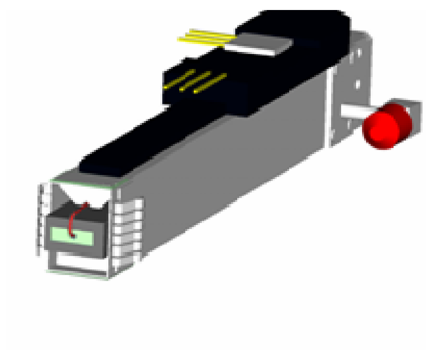

Figure 4. Drawing of a Spy-1B/D Phase Shifter
(Source: Used with Permission from Lockheed Martin, 2006)

Beams are formed by shifting the phase of the signal emitted from each radiating element to provide constructive/destructive interference so as to steer the beams in the desired direction. In Figure 5, both radiating elements are fed with the same phase. In Figure 6, both elements are fed with different phases. The signal achieves maximum gain by constructive interference in the main direction. The beam sharpness is improved by the destructive interference.

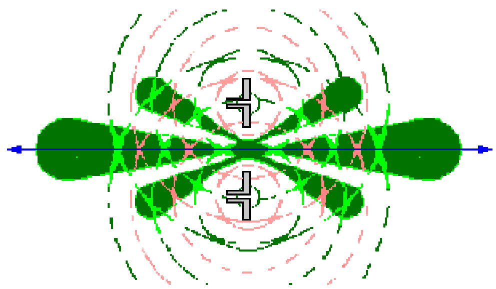

Figure 5. Two Elements Fed with the Same Phase
(Source: From Radar Tutorial, 2006)

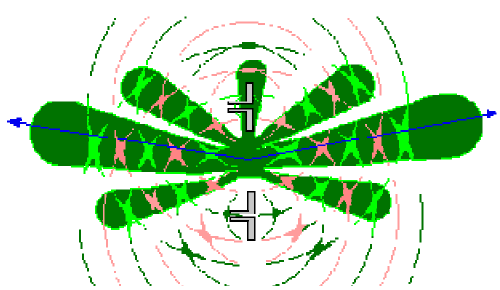

Figure 6. Two Elements Fed with Different Phases
(Source: From Radar Tutorial, 2006)

C. ANATOMY OF AN AEGIS RADAR PHASE SHIFTER

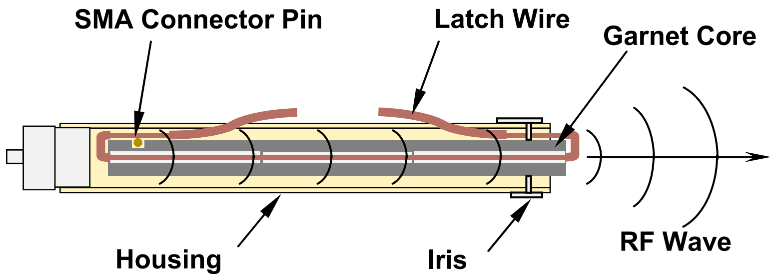

Figure 7. Cross-section of a Phase Shifter Assembly
(Source: Used with Permission from Lockheed Martin, 2006)

- **Phase Shifter Assembly operates as a waveguide**
  - Wave is launched into cavity from center pin of SMA connector
  - Aluminum housing establishes waveguide cavity
  - Phase shifter and faceplate form the radiating element for the antenna
- **Voltage is applied to latch wire to change phase**
  - Magnetic field from latch wire current establishes magnetic dipole within ferrite
  - Magnetic field strength is proportional to latch-wire current
  - Traveling wave interacts with dipole moment in ferrite, changing the wave's effective phase
  - Each phase shifter has a phase slope and temperature compensation resistor attached, which compensate for individual performance
- **Phased-array antenna beam is steered by controlling phase of transmitted wave at each radiating element**

D. TOTAL OWNERSHIP COST (TOC)

Readiness is a critical parameter of all Department of Defense (DoD) weapon systems. If a system is not ready, its performance characteristics are of no use. Each weapon system has an expected readiness rate that must be maintained for national security. Readiness can be achieved by building highly reliable weapon systems or, if the systems are not highly reliable, by supporting them with an extensive logistics system that can ensure spare parts and other support items are available as needed. In essence, the cost of a product's readiness is the cost to develop, produce, operate and maintain that system. For example, in 2001, the total cost for the AEGIS Weapons System was at \$42.7 billion, the predominant cost driver being operations and support (O&S) at \$22.2 billion (Jane's.com, 2006).

Traditionally, development and production (acquisition costs) have accounted for about 28% of a weapon's total ownership costs, while O&S costs account for about 72% (Figure 8). For a number of years, the DoD's goal has been to spend less on system support and more on development and procurement in order to modernize weapon systems. But in fact, growth in operating and support costs has limited the DoD's buying power. DoD officials have cited shortages of spare parts and unreliable equipment as reasons for low mission-capable rates for some weapons. As a result, some modernization has been postponed in order to pay high and unexpected O&S costs (US GAO, 2003, February).

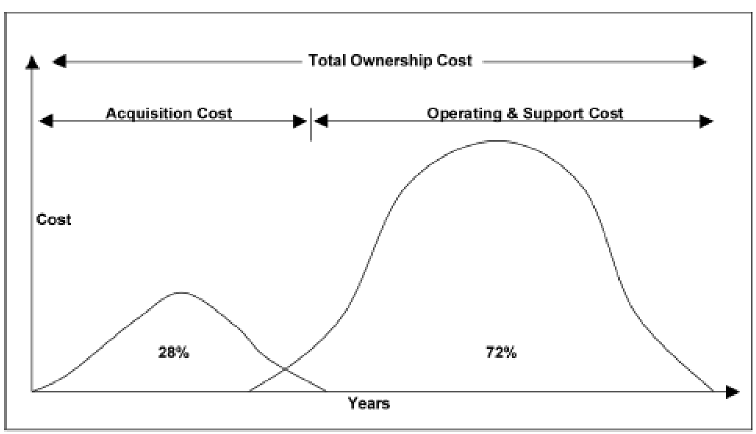

Figure 8. Nominal Lifecycle Cost of Typical DoD Acquisition Program with a 30-year Service Life (Source: From GAO, 2003, February)

Total Ownership Cost has two definitions; the first is very broad, seen from the DoD or Service perspective. The second definition is deliberately written from the vantage point of the program manager of a warfighting system. For this discussion, the research will focus on the second definition:

> Defense Systems TOC is defined as Life Cycle Cost (LCC). LCC (per DOD 5000.4M) includes not only acquisition program direct costs, but also the indirect costs attributable to the acquisition program (i.e., costs that would not occur if the program did not exist). For example, indirect costs would include the infrastructure that plans, manages, and executes a program over its full life and common support items and systems. The responsibility of program managers in support of reducing DOD TOC is the continuous reduction of LCC for their systems. (Boudreau & Naegle, 2003, September)

Pursuit of Total Ownership Cost reduction at the level of the warfighting system may be separated into two major approaches that are connected, end-to-end, along a lifecycle time line. During the development phases, the effort or process is called Cost As an Independent Variable (CAIV). For systems in the field or fleet, the process becomes Reduction of Total Ownership Cost (R-TOC). Figure 9 is a typical depiction of the CAIV/R-TOC relationship (Kaye, Sobota, Graham & Gotwald, 2000).

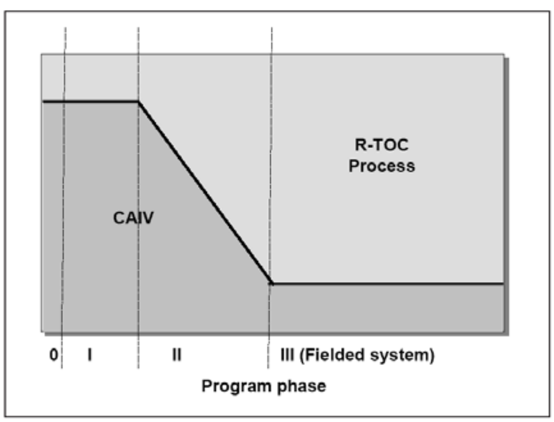

Figure 9. CAIV/R-TOC Transition
(Source: From Kaye, Sobota, Graham & Gotwald, 2000)

The first approach, Cost As an Independent Variable (CAIV), addresses Total Ownership Cost during the warfighting system's developmental phases, beginning with the Concept Refinement phase. The focus of CAIV is to establish cost targets based on affordability and requirements and then to manage to those targets, thereby controlling TOC (Boudreau & Naegle, 2003).

The second approach, Reduction of Total Ownership Costs (R-TOC), focuses on the reduction of average procurement unit cost (APUC), and weapon system operating & support (O&S) costs. R-TOC is employed as the warfighting system is produced and placed in service. Examples of R-TOC would be a value engineering change proposal (VECP) to reduce the cost of manufacturing a component by improving the process yield or by reducing O&S costs by improving the reliability of an expensive system or component. Although R-TOC initiatives are more effective when performed early in development, R-TOC can be effective throughout the system's lifecycle (Boudreau & Naegle, 2003).

1. Cost Drivers

Operating and support costs may be dramatically reduced by identifying cost drivers and correcting them—often, but not always, through redesign. The most efficient time to accomplish this is during the pre-acquisition and development phases while the system is only a paper design and may be changed relatively inexpensively. However, acquisition cost drivers that are discovered during the production phase also may lead to redesign or other actions to reduce the APUC, or may reduce the cost of manufacturing by improving the process yield to save or avoid future expenditures.

Since Lockheed Martin had so much design success (phase shifters proven to be 100% reliable, therefore, never requiring reliability metrics or O&S costs), the focus in this study will be on the latter—acquisition costs, namely: the design and redesign of the SPY-1 phase shifter (which dramatically improved performance without increasing the APUC), and the reduction of costs to manufacture SPY 1-B/D phase shifters by improving the process yield. Additionally, this research will present various process-improvement programs used to reduce "touch-labor" and improvements to programs that

affected phase-shifter production either directly or indirectly, i.e., consolidated purchasing, lean and six sigma, productivity improvement projects, etc.

E. CONTRACTING PROCESSES AND INFLUENCES

1. Background

Contracting policy, processes and procedures can have significant and highly influential results on all types of programs. Contracting and contract incentives have had influence over Government programs since the early 1900s. One of the earliest appearances of the contract incentive was the arrangement utilized in the contract for the Wright Brothers' aircraft. The century saw many twists and turns in the form of changes in preferred contract type and use of incentives. In the 1940's, the Navy pushed to change most of its large ship, airframe and ordnance contracts from cost-reimbursable to fixed-price contracts. This scenario was repeated throughout the realm of Government contracting to fit the policy of the day. For example, in the 1950's, the contract type that dominated the landscape was cost reimbursable to enable our defense base to push forward rapidly in technology to gain advantages over the Soviets. In the 1960's, in the face of increasingly growing numbers of contract overruns, budget pressures pushed the contracting communities away from cost-reimbursable contracting. The fixed-price contracting arrangement was now again in vogue. During this time, fixed-price arrangements failed to curtail cost overruns because, in many instances, the contractor assumed too much risk for the particular work being accomplished, and contracts had to eventually be altered to facilitate system delivery. The fixed-price contract again fell into the realm of disuse until the 1980s. In the 1990s, a deliberate reform movement worked to redefine the Government and contractor relationship. A return to cost-reimbursement development contracts in order to more equitably balance risk with contract type where appropriate began during this period. In addition, the use of fixed-price contracts for commercial items and other appropriate efforts was retained. This shifting from one-type-fits-all contracting to specific contract types being used appropriately resulted in contracts wherein the rewards were commensurate with the risks for the contractor and superior performance for the Government (Venable, 2000, December). Finally, the federal procurement system underwent sweeping change and reform that included the *Federal Acquisition Streamlining Act* (*FASA*) and the *Federal Acquisition Reform Act*

(*FARA*). These pieces of legislation revolutionized the federal procurement apparatus and promoted both innovation and the idea of the contracting officer functioning as a business advisor rather than just as a "speed bump" that enforced procurement regulation and statutes.

Throughout the century, contract policy and contract incentive use evolved and adapted to meet requirements and satisfy other Governmental policy objectives. Some evolutions led to less-than-desirable results; others led to great examples for future successes to emulate. Overall, these changes in contracting policies and processes contributed to the development of successful acquisition and contracting strategies that are still utilized in today's weapon system programs and will most undoubtedly be used for future weapon systems.

Overall, with respect to contract type or contract incentive, while the program or contracting authority determines what contract type or incentive should be used, the PM must understand each method or process available and apply the applicable criteria for use. The only way for a program to reap the benefits of any contract type or incentive is to use and apply them appropriately as they correspond to the program, program objective, requirements, contractor objectives, and other internal and external forces surrounding the decision-making environment.

2. Acquisition and Contracting Contextual Framework

The natural prerequisite to using effective and appropriate contracting methods, types and incentives is to understand the different choices available to the contracting officer and their particular criteria for use. This section will generally describe contracting types available to the contracting officer and incentives that could be used to promote superior contractor performance. It will by no means include an exhaustive list of contract incentives or newer, more progressive and innovative incentives available for use today. It will outline the basic contract incentives that have the potential to motivate contractors to improve performance with respect to cost, schedule, or delivery and include a history of use in Government contracting. These incentives are also outlined in the *Federal Acquisition Regulation* (*FAR*).

a. Contract Types

There are essentially two over-arching contract types available to the contracting officer. On one end, there are cost-reimbursable contracts; on the other end of the spectrum is fixed-price contracts. Cost-reimbursable contracts place maximum risk upon the Government because the contractor is only obliged to put forth its best effort and possibly may not even deliver the end product. In addition, the Government pays all allocable, allowable, and reasonable costs associated with the effort and contract. Although these types of contracts include statutory limitations on fees paid to the contractor, there is no real motivating factor to influence the contractor to control costs. These types of contracts are generally reserved for efforts that are developmental and research driven in nature, or situations in which there is an increased amount of risk because of unknowns and unproven concepts or technologies.

The fixed-price contract type shifts most of the risk to the contractor performing the service or delivering the product. This is because the contractor must deliver the product or service, and only the final negotiated price is paid (which may be less than costs incurred by the contractor). However, there is no limit on the potential profit earned by the contractor, either, and the contractor can increase the profit yielded by lowering the costs incurred during performance of the contract. These contract types are generally used on commercial and lower-risk or proven technology-driven requirements where risks are mostly known and manageable.

b. Contract Incentives

The basic fundamental of incentive contracting is to direct contractor performance in the manner desired and to exceed minimum contract requirements in one or multiple performance attributes. The two basic types of incentive methods used are formula-based incentives and award-fee incentives.

Formula-based incentives utilize cost and fee or profit-specific targets that correspond to a particular cost and savings sharing relationship between the Government and the contractor. These targets and the ratio of costs or savings shared between the two parties determine the fee or profit benefit from contractor performance results. Cost-reimbursable incentive contracts or Cost Plus Incentive Fee (CPIF) contracts have a minimum and maximum fee with no ceiling price due to the reimbursable nature of the

contract. Fixed-price Incentive (FPI) contracts incorporate use of a ceiling price that could possibly lead the contractor to assume 100% of the cost responsibility when total price surpasses what is called the Point of Total Assumption (PTA). This is the point at which every additional dollar spent by the contractor eliminates a dollar of potential profit. This is the point at which the FPI reverts to a FFP contract. Contracts that use the formula-based approach sometimes incorporate performance, schedule or even additional cost incentives to motivate the contractor to superior performance. The performance characteristics of the contract and the contractor must be amenable to being objectively measured in order to ascertain the level at which the contractor was able to perform the contract requirements.

Award-fee contract arrangements can be characterized by flexibility, subjective evaluation of contractor performance, and administratively intensive contract management processes. An award-fee contract, if cost-reimbursable, usually has a small base fee that establishes the minimum amount of fee available to the contractor for performing the contract. In some cases, the base fee may be zero dollars, depending on the intention of the contract strategy. In addition to the base fee, there is a maximum fee that a contractor can earn in an award-fee contract. The difference between the two fees accounts for the award fee that is usually allocated for award to the contractor over a number of periods during the term of the contract. While the award-fee option offers some increased flexibility to the Government over formula-based incentive contracts, the major drawback is the significance of administration required to manage the contract and, specifically, to operate the award-fee decision mechanisms required like the PEB.

c. Business and Management Issues

Other factors can significantly influence the success of any contract strategy. Many programs have failed because the parties involved failed to recognize the interest of the other and, therefore, opportunities for mutual benefit and success. Divergent motivating factors between the parties can sabotage the ultimate goal of any incentives or contract arrangement and push the parties to pursue their own interests rather than the best interests of the program. Arrangements in which both parties have a vested and shared interest in the success or failure of the program are more likely to work toward common goals and produce successful outcomes.

Achievement of desired program results involves a conscious effort to balance a series of tradeoffs. Accomplishment of this balance among the different tradeoffs depends on the effective translation of the program's goals into an effective contract strategy. Success will depend on both parties understanding the differing motivations at play and the level of balance developed in the incentive relationship between the two. To attain balance, the correct incentives must be identified and communicated effectively to all parties. The Government communicates to the contractor management through the actual contract, and the contractor management communicates the incentives and program goals to its employees through the organization. The objective should be to engage the right incentives that will effectively motivate the contractor organization and each employee.

F. ABOUT LOCKHEED MARTIN AT MOORESTOWN

Lockheed Martin Corporation (LMCO) is principally engaged in research, development, manufacture, integration and sustainment of advanced technology systems, products, and services. The corporation serves customers worldwide in defense and commercial markets, with its principal customers being agencies of the US Government. With its corporate headquarters in Bethesda, Maryland, LMCO is organized into five business areas: Aeronautics, Electronic Systems, Information & Technology Services, Integrated Systems & Solutions, and Space Systems. LMCO employs 135,000 personnel at 939 facilities worldwide, and achieved $37.2 billion in sales for 2005 (Figure 10).

Lockheed Martin Maritime Systems & Sensors (MS2) in Moorestown, New Jersey, is part of the Electronic Systems business area which manages complex programs and provides integrated hardware and software solutions to ensure the mission readiness of armed forces and government agencies worldwide; this facility achieved $10.6 billion in sales for 2005. The MS2 facility was established in 1953 as part of RCA Corporation and later merged with General Electric-Aerospace Group, was sold to Martin Marietta in 1992 and merged with Lockheed in 1995.

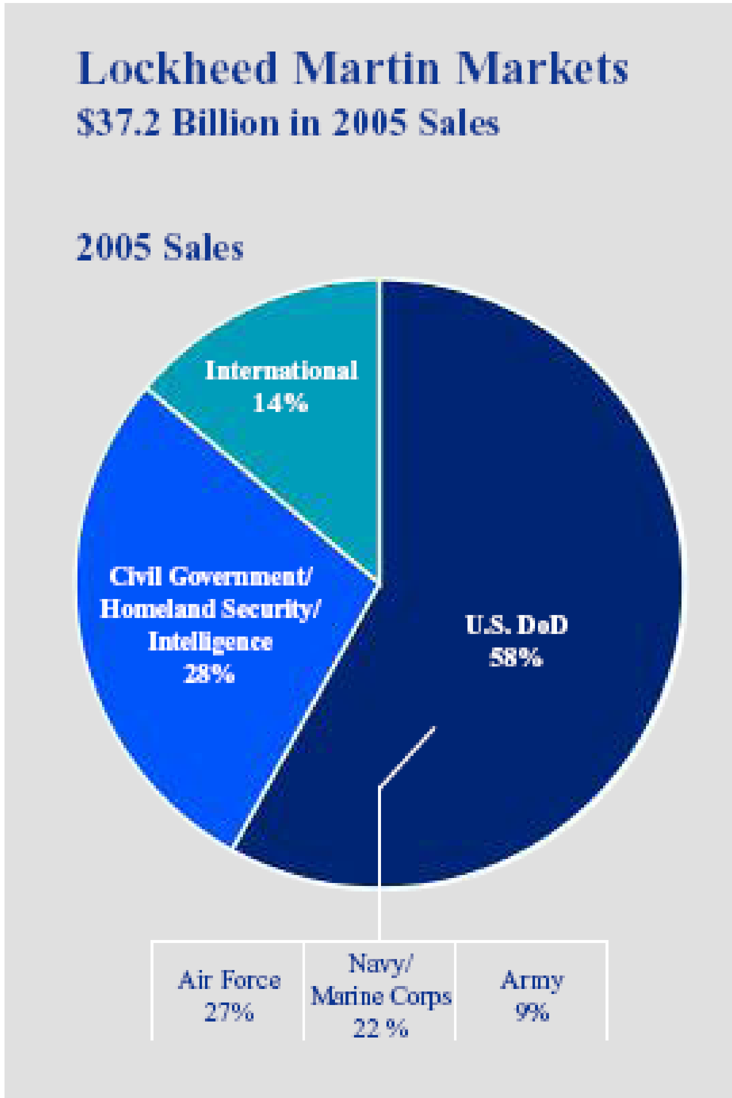

Figure 10. Lockheed Martin Sales for 2005
(Source: From Lockheed Martin, 2006)

LMCO-Moorestown is the prime contractor for manufacturing and integration of the Aegis Weapons System and Aegis Depot Operations for the Navy. Its successful history in large-scale systems integration, radar technology, software development, microelectronics, lifetime support, vertical launching systems, and fire-control systems enabled the company to establish a solid foundation for creating future innovative solutions.

II. SPY-1A PHASE SHIFTER

A. PHASE SHIFTER BACKGROUND

A phase shifter is a two-port device whose basic function is to provide a change in phase of RF signal with minimal attenuation. Basically, there are two types of phase shifters: mechanical and electronic. From the late 1940s up to the early 1960s, prior to the development of electronically variable phase shifters, all phase-shifting requirements including those of beam-steering array antennas were mostly met by mechanical phase shifters. In 1957, Reggia and Spencer reported the first electronically variable ferrite phase shifter, which was employed in an operational phased array (Koul & Bhat, 1991). The 1960s saw the emergence of another important type of phase shifter—the semiconductor diode phase shifter. Since then, significant advances have taken place in both ferrite and semiconductor diode phase shifters, resulting in a wide variety of practical devices. Major growth of phase-shifter technology came from its known potential utility in phased arrays.

A typical phased array may have thousands of radiating elements, and with each antenna element connected to an electronically variable phase shifter, the array acquires the basic capability for inertia-less switching or scanning of the radiated beam with minimal time. With this capacity, the array achieves complete flexibility to perform multiple functions in 3-D space, interlaced in time and even simultaneously. The evolution of phased-array technology to its present sophisticated form is strongly based on the development of electronically variable phase shifters. In turn, new areas of application have opened up in radar, communication, and civilian sectors, demanding newer techniques and technologies for phase shifters. In addition to ferrite and semiconductor diode phase shifters, several other types have emerged in recent years; these, however, are not the focus of this research, and, hence, will not be discussed.

B. THE BIG BREAKTHROUGH

Due to lack of electronic media available from the 1970s, and multiple corporate mergers (RCA/GE/Martin Marietta/Lockheed) spanning three decades, detailed engineering/production data of the AEGIS Weapons System transition from the EDM-1 to the SPY-1A is virtually non-existent or not available. Research relating to this effort is based on the recollections of current and retired production engineers and mangers from Lockheed Martin at Moorestown.

In the 1960s and '70s, ferrite phase shifters were preferred for the large phased-array radars. However, they were extremely expensive. The first phase shifters used in EDM-1 were in the neighborhood of $2000 per unit in 1974 dollars. One phased-array radar antenna requires 4500 phase shifters, and one AEGIS combatant requires four phased arrays, thus, totaling approximately $36 million in phase shifters alone. In 2006 dollars, this equates to approximately $148 million, clearly representing a significant cost for a single part in one system on a AEGIS equipped ship. Although AEGIS was a huge leap in National Defense, RCA knew that ferrite phase shifters would have far-reaching effects on acquisition management, design, and lifecycle support of a modern navy.

In an effort to drive down AEGIS Weapons System costs, RCA embarked in a 2-3 year effort to productize the phase shifter, that is, something that could be practically specified, repeatable, and producible. This productization effort resulted in RCA designing its own version of the ferrite phase shifter for use in the next generation of SPY-1 Radars.

The phase shifter comprises a magnetic material toroid (shown in Figure 11) shape with integral dielectric inserts that is itself inserted into an extruded rectangular metal tube waveguide. The magnetic toroid is a mixed oxide, ceramic-like material possessing ferromagnetic properties. The phase shifter design was required to meet demanding electrical requirements to control the amplitude and phase of the radiated waveform at the antenna aperture to achieve a narrow radar beam with low antenna sidelobes at moderately high power. Selection of the materials comprising the phase shifter required extensive research and testing of available materials in the industry. The requirement to be operational in a temperature between 140 and 160 degrees Fahrenheit

led to the decision to use a temperature-stabilized garnet rather than a ferrite; the latter is generally less expensive, but also less stable with temperature.

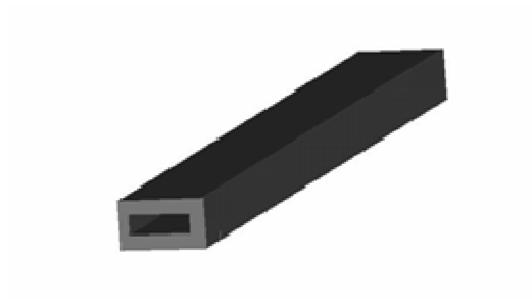

Figure 11. Garnet Used in AN/SPY-1 Phased-array Phase Shifters
(Source: Used with Permission from Lockheed Martin, 2006)

RCA was able to meet the cost objective to produce one phase shifter unit for approximately \$200—a monumental effort considering it brought down the cost of one ship-set (18,000 units) from approximately \$148 million to approximately \$15 million (2006 dollars). Although RCA designed the phase shifter for AEGIS, critical materials for the phase shifter were procured from other companies. The garnet material was provided by Trans Tech who has continued to provide all of the garnet material for AEGIS production.

Assembly of the phase shifter has always been a significant challenge due to the sensitive nature of the material interactions between the garnet material, the aluminum housing, and ancillary RF and logic control wire interfaces. A highly skilled assembly team using advanced manufacturing process control techniques has continually managed this process closely to provide the high yields necessary to achieve the demanding cost requirements.

C. NEW REQUIREMENTS FOR SPY-1B

Although the AEGIS SPY-1A radar was a huge success, the Navy continued to push RCA throughout the 1980's to improve phase-shifter insertion loss, bit-phase shifting, and differential phase error—ultimately reducing sidelobe levels (Figure 12). Low sidelobes were among the highest priorities for several reasons: reduction of radar and communications intercept probability, reduction of radar clutter and jammer

vulnerability, and increasing spectrum congestion in satellite transmissions (Lockheed Martin, 2006). The big challenge for RCA was how to meet the Navy's new performance requirements and keep down costs.

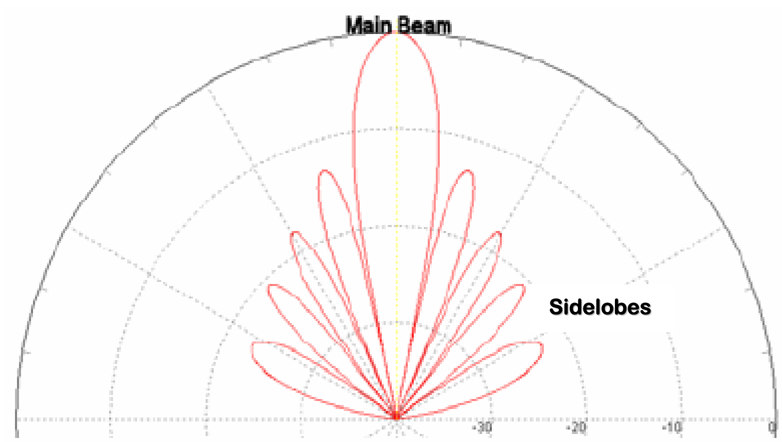

Figure 12. Depiction of Main Beam-sidelobe relation
(Source: After Radar Tutorial, 2006)

Differential Phase Error is the root-mean-square (rms) phase-shift error due to variations with frequency, phase state, power, and temperature. When considering a large number of phase shifters (4500 in one array), the calculation of this error may include variations from unit to unit. Phase error reduces the antenna gain in a transmitting array and raises sidelobes in a receiving array. The rms phase error permissible for the SPY-1A phase shifter was ≤ 5.8 deg rms (Lockheed Martin, 2006).

The Navy's new differential phase error performance parameter for SPY-1B was ≤ 2.1 deg rms (Lockheed Martin, 2006). This was a 64% improvement requirement over the SPY-1A. In order to achieve these numbers, RCA had to make one major modification and one major trade-off—increase phase-shifter bit capacity, and allow more insertion loss.

Digital (bit) Phase Shifters offer greater speed of operation and ease in interface with control computers. The number of bits needed is determined by the radar design requirements—in particular, the number of radiating elements, element spacing, and the scan-angle increment. Typical phased arrays generally use 3 or 4-bit phase shifters (Figure 13) as a compromise between cost, size, and system performance. SPY-1A used

a 4-bit design. However, up to 8-bit phase shifters have been used for applications that demand very low sidelobes with fewer number of antenna elements. In an effort to improve performance while maintaining lower costs, RCA decided to use 6 bits with the SPY-1B.

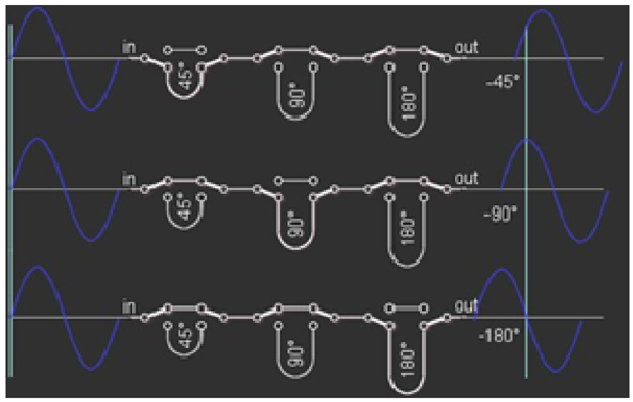

Figure 13. A 3-bit Phase Shifter

Note: The illustration shows the basic delays each phase shifter can introduce. A central computer calculates the proper phase delay for each of the radiating elements and switches in the appropriate combination of phase-shifter pathways. The cables delay the wave, thereby shifting the relative phase of the output. (Source: From Radar Tutorial, 2006)

Insertion loss should be as low as possible. In the transmitter mode, insertion loss in the phase shifter results in loss of transmitter power and heating of the phase shifter due to power dissipation. In the receiver mode, it results in lowering the signal-to-noise-ratio. The max insertion loss permissible in the SPY-1A phase shifter was ≤ 1.15 dB at the high and low test frequencies, ≤ 0.85 dB everywhere else (Lockheed Martin, 2006). RCA's max insertion loss permissible for SPY-1B was ≤ 1.45 dB at the high and low test frequencies, ≤ 1.35 dB everywhere else (Lockheed Martin, 2006). This was 26% and 59%—respectively, more insertion loss allowable over the SPY-1A.

The end result was Baseline 3, which included the lighter AN/SPY-1B radar—a system that provided a significant improvement in the detection capabilities of the AEGIS Weapons System. This radar incorporated significant advances over the earlier SPY-1A radar with the improved radiating characteristics, new AN/UYQ-21 consoles, and lower sidelobes—increasing its resistance to enemy Electronic Countermeasures (ECM). Additionally, with the SPY-1B radar and the ship's MK 99 Fire-control System,

the ship could guide its Standard Missile to intercept hostile aircraft and missiles at extended ranges.

The SPY-1B phase shifter was as big a breakthrough as was the SPY-1A in that RCA was able to increase phase-shifter performance by leaps and bounds for the next generation of radars, yet do it without increasing the average unit procurement costs. CG-59 was the Navy's first cruiser equipped with the SPY-1B radar system (Figure 14).

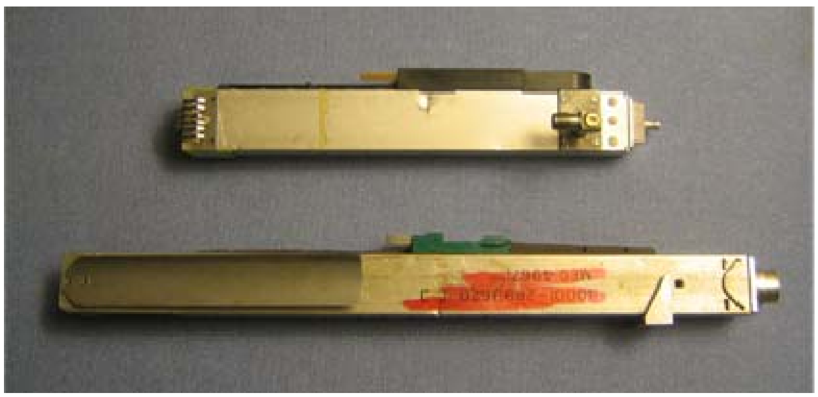

Figure 14. Comparison of SPY-1B (above) vs. SPY-1A (below)
(Source: Used with Permission from Lockheed Martin, 2006)

1. Ferrite vs. Diode: RCA Wins AEGIS Destroyer Contract

In the 1980s, when RCA was working on the next generation of the AN/SPY-1B Radar for the Navy's new AEGIS Destroyer program, it found itself in competition with Hughes Corporation. Hughes proposed an alternate approach using semiconductor diode components. Production costs of a diode phase shifter was less than that of a garnet unit because the diode phase shifter was amenable to mass production and printed circuit techniques, whereas the garnet phase shifter required highly skilled labor. Therefore, Hughes entered into fierce competition with RCA for the DDG-51 Class AEGIS Weapons System contract (Lockheed Martin, 2006). However, although garnet was more expensive to produce, RCA proved to the Navy that garnet phase shifters were clearly the best value.

Due to their large variations in reliability, the choice of a garnet or diode phase shifter had a major effect on not only the antenna design but on the radar. The garnet phase shifter basically has no failure mechanisms. Most of the reliability considerations

for a garnet phase shifter are related to the driver. The diode phase shifter is subject to diode burnout and failure mechanisms in both the phase shifter and the driver. Additionally, the type of phase shifter used and the manner of its use is of more importance in the very low-sidelobe phased-array antennas required by the Navy. In most cases, the diode is either in or exceedingly close to the radiation element and subject to any electromagnetic pulse (EMP) impinging on the aperture. During the Cold War, this proximity was particularly important if nuclear effects were part of the operation environment (Billetter, 1989). Unless radiation-hardened diodes were used or the phase shifter was isolated from the EMP, there is a high likelihood that the diodes may burn up.

In 1984, RCA won the $233 million SPY-1B government contract (Reuters, 1984). RCA's “best value” pitch proved its worth. To date, 23 years—76 AEGIS capable US Cruisers and Destroyers later—a garnet phase shifter has never been replaced due to failure (Lockheed Martin, 2006).

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III. SPY-1B/D PRODUCTION IMPROVEMENT PROCESSES (PIP)

A. BACKGROUND

Since 1984, there have been many process improvement initiatives to improve process yield and to reduce touch labor of the SPY-1B/D phase shifter. This chapter will discuss some of the more important initiatives and their impact on the APUC. Although this is probably the most important chapter of the case study, it lacks substantial quantitative cost data. The research visit at LMCO-Moorestown was very productive, found personnel accommodating, management was very friendly; employees even made time to show the researcher around the facility. However, it was difficult for LMCO, in our research efforts, to ascertain detailed quantitative cost data in specific areas that improved process yield and reduced touch labor. Therefore, this chapter provides only some very general graphs, some of which are incomplete. Yet, though these graphs may be incomplete, they still provide a good overarching snap-shot to illustrate the impact of process yield and touch labor on costs.

The first chart (Figure 15) shows how LMCO-Moorestown brought the APUC of a phase shifter from \$200 in 1984 down to almost \$100 in 2002. The APUC for phase shifter in 2006 is now \$80 (\$1.44 million per ship-set). If we convert the \$200 APUC in 1984 to 2006 dollars, we get \$5.91 million per ship-set. After the conversion to 2006, we can see a substantial reduction in APUC of \$4.47 million (76%)—a sizable cost reduction considering this is a single part in one system on an AEGIS equipped ship.

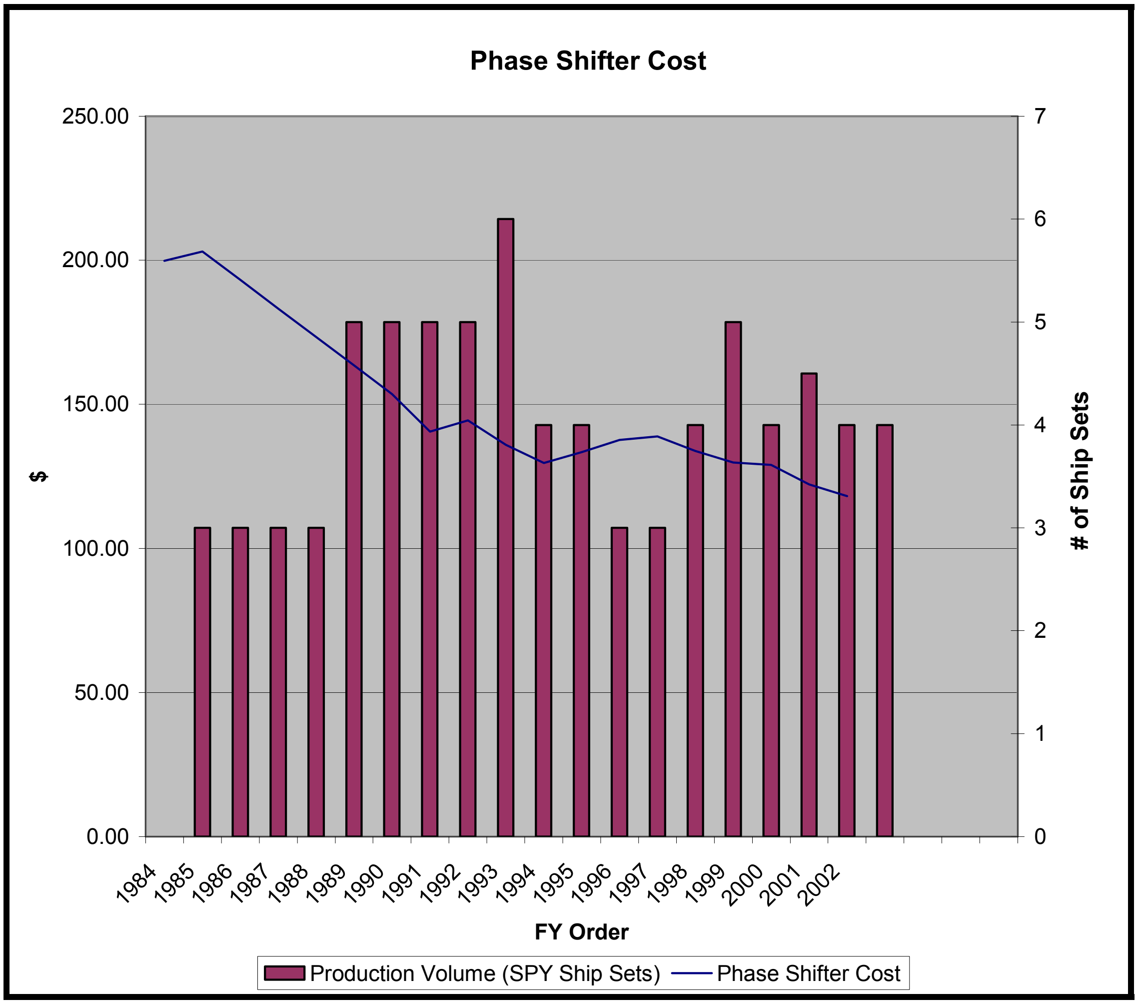

Figure 15. Phase Shifter Cost per Unit
(Source: Used with Permission from Lockheed Martin, 2006)

B. PROCESS YIELD

1. Defect and Scrap Reduction

Scrap generation and defect production are important conditions when evaluating a company's performance. LMCO-Moorestown established a program in 1991 to both measure and reduce these parameters. For scrap, prior to 1991, there was a limited breakdown of collected data, and the data was not in a format that allowed meaningful analysis (Office of Naval Research, 1995, October). Review of the data was led by Engineering Management. However, little of the information was relayed to floor personnel where it could produce the greatest impact.

LMCO-Moorestown has since established multifunctional teams in each work center. Each team brainstorms a list of metrics for the work center that are monitored, including defects and scrap. Performance is then measured against the metrics weekly. An important aspect of this effort includes the linking of the company suggestion program to team efforts and performance.

Benefits have been demonstrated throughout the company. For example, phase-shifter defect yield of a hoped-for 80% in the 1970s improved to 99.5% in 2006 (Lockheed Martin, 2006). Scrap costs have been reduced by 60% from 1994 through 2006 (Figure 16). In addition, this approach has yielded intangible benefits, such as improved problem solving and corrective action skills, increased sense of ownership by the team, lower costs, higher quality, and a more educated workforce.

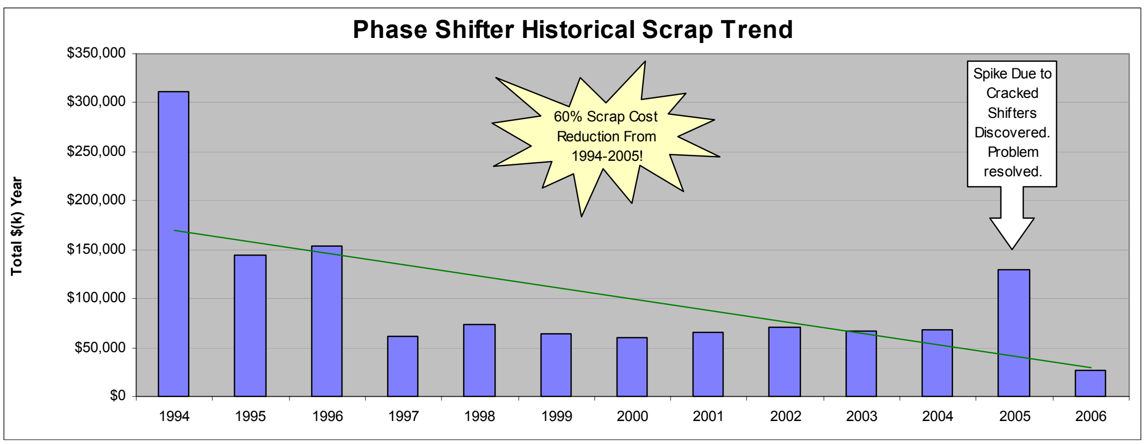

Figure 16. Phase Shifter Historical Scrap Trend 1994-2006
(Source: Used with Permission from Lockheed Martin, 2006)

2. Type K/Blue- and Orange-stripe Phase Shifters

Type K/Blue- and Orange-stripe Phase Shifters are phase shifters with suspect loss or phase characteristics as determined during testing. However, in an effort to reduce scrap, other uses for these phase shifters have been realized. Specifically:

- *Type K*. Type Ks are phase shifters with acceptable Voltage Standing Wave Ratio (VSWR). The performance of the other parameters is irrelevant. 300 Type Ks go into every antenna, 150 in each upper corner. They are terminated and not hooked up to any driver circuit; hence, the phase characteristics are

inconsequential because the unit isn't shifted. The loss characteristics are inconsequential as well, because there's no RF connection.

The side-lobe blanker (SLB) units are "buried" in amongst the Type Ks. Without going into array physics, the arrangement provides better SLB performance by, in effect, making the SLB element look as if it's in an infinite array. This makes things work better and with more clarity. The mutual coupling between the SLB and the Ks makes that happen. For that reason, the only concern is VSWR, which, if too high would result in unwanted reflections between the elements.

The SPY-1B array was designed for these units. When there is not enough units that have suspect loss or phase characteristics, normal "in-specification" units are used.

- *Blue Stripe*. Sometime in the mid 1980s, LMCO had a large number of units come through with excessive differential phase error. Analysis showed that units with differential phase error between 2.1 and 2.8 deg rms at any frequency still had limited use (marked with a blue stripe), 2.1 deg rms being the high limit for "in-spec" phase shifters (unmarked).

Differential phase error directly influences sidelobes; therefore, using units with high differential phase error could result in a non-compliant array. LMCO built an array with 25% Blue Stripes to demonstrate their usefulness. LMCO changed the specification, and now allow up to 25% of the phase shifters in an array to be Blue Stripes, again reducing scrap and improving process yield. LMCO's simulations showed that this would still allow sufficient margin in array side-lobe performance to accommodate any other variations that might arise in production.

The term "Blue Stripe" comes from the way the units are marked and identified after testing.

- *Orange Stripe*. Orange-stripe phase shifters have higher insertion loss than "in-spec" units. The average loss spec is 1.45 dB at the high and low test frequencies, 1.35 dB everywhere else. The Orange Stripe units are allowed an insertion loss of up to 1.75 dB at the high frequency. Increased loss affects gain. A higher variation in loss, as one would see when blending in units with higher loss than normal, increases side-lobe levels. For these and other reasons, Orange Stripes are only used around the periphery of the antenna, where they have the least impact on performance.

  Orange Stripes came about in 2003 when the phase shifters started to show excessive loss at the high end of the frequency band. LMCO found that the antenna could tolerate them in limited quantities.

  The Orange Stripe idea was a variation on the Blue Stripe. The testers were already used to the idea of marking some of the units. Making an additional color category was a natural fit.

3. Replacing Green Epoxy with UV Acrylic

Green epoxy was originally used to hold two irises in place inside the phase-shifter housing. However, there was concern because the iris would occasionally dislodge from the garnet during testing, rendering the phase shifter scrap (Figure 17). The iris is highly important because it functions as a tuning element in the waveguide cavity.

As a remedy, and as a defect yield and cost reduction improvement, LMCO-Moorestown changed from the green epoxy to a UV, acrylic material. The UV acrylic is less expensive and provides more flexibility to prevent the iris from dislodging. Not only did this reduce defect yield, but it also reduced cycle-time. Additionally, the green epoxy required 24 hours to cure; the UV acrylic literally takes seconds. The UV acrylic is an adhesive applied to the sides of the garnet, cured by a 60-second exposure to UV radiation in a UV-cure chamber.

In addition to the UV-cured adhesive applied to hold on the iris, LMCO also implemented an employee suggestion of another defect yield reducing process. The

suggestion was to apply the adhesive to the end of the garnet at the same time it was applied to the sides to act as a protective coating to prevent bench-handling chips.

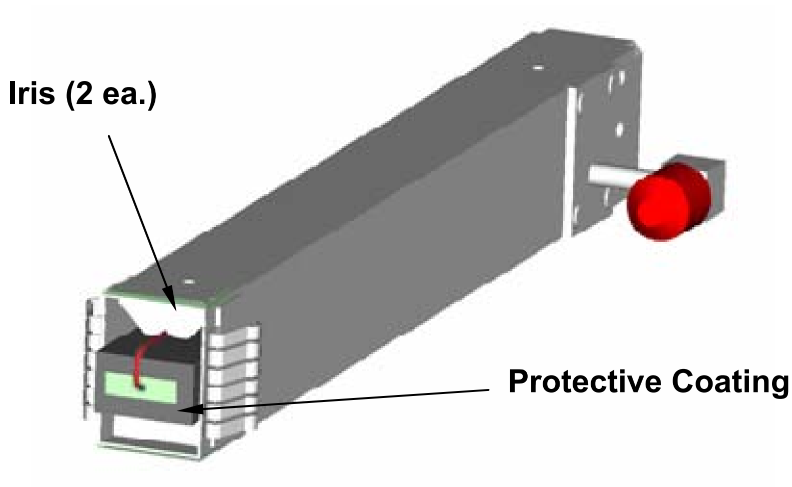

Figure 17. Phase Shifter Showing Garnet/Iris Relation
(Source Used with Permission: from Lockheed Martin, 2006)

C. TOUCH-LABOR

Changes in the defense environment since the mid-1980s affected most Government contractors. In 1989, LMCO-Moorestown responded to changes by abolishing thousands of positions. However, the Local 106 union moved to team with LMCO in a partnership as both sides realized they had to work together to remain a viable business. This initiative demonstrated LMCO's determination to maintain a level workforce. LMCO listened to new ideas, facilitated implementation, and opened lines of communication. Aggressive goals were set—and exceeded—such as reducing touch labor by 26%. By implementing the initiative, what was scheduled to become additional outsourced work on components for the AEGIS system translated into the retention of 400 labor positions planned for elimination (Office of Naval Research, 1995, October). Today, touch labor is down by 40% in phase shifters alone (Figure 18). The remainder of this Chapter discusses some of the larger contributors to reducing touch labor of phase shifters since 1990.

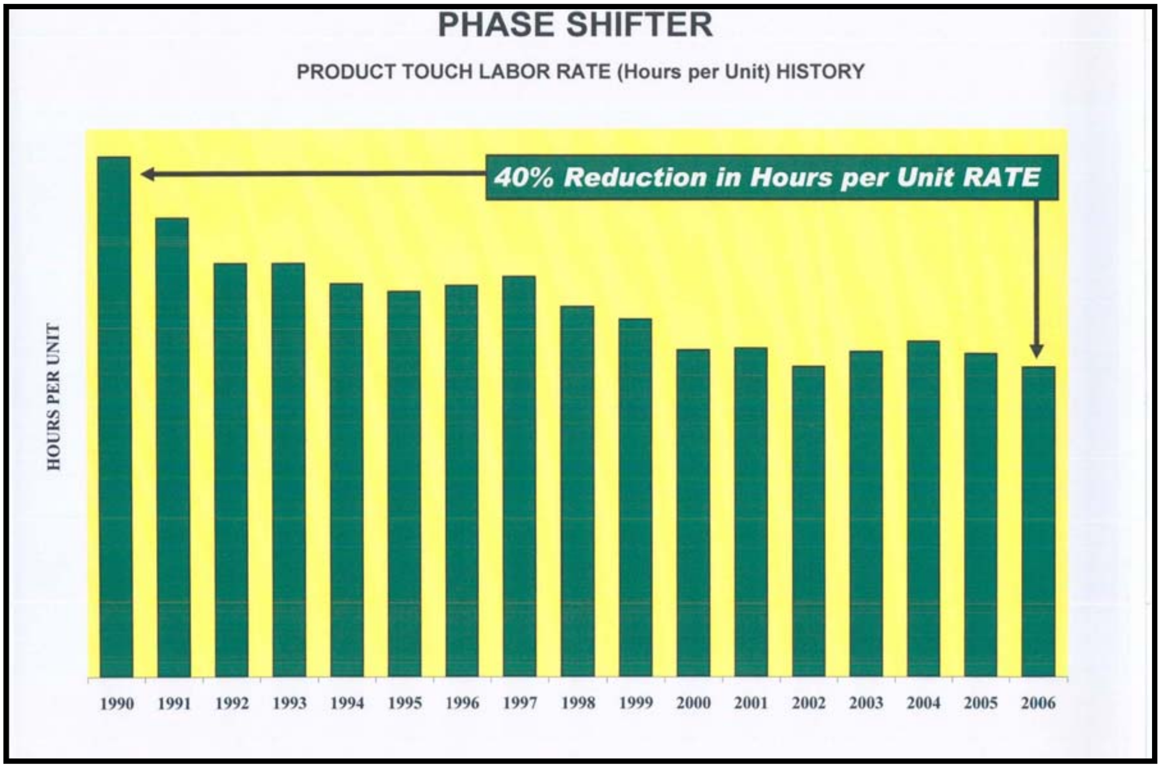

Figure 18. Phase Shifter Touch Labor Rate History 1990-2006
(Source: Used with Permission from Lockheed Martin, 2006)

1. UV Acrylic Cure Process

The UV acrylic process was previously discussed in the process yield section, however, because of reductions in touch labor, it warrants further discussion. The iris epoxy cure process was labor intensive prior to the introduction of the UV acrylic. The epoxy was a two-part adhesive that required one operator 16 hours a week to mix enough material for one week's production of phase shifters. Additionally, the two-part epoxy was time-sensitive once mixed; so, material that didn't get used expired rapidly. The UV acrylic is a one-part material which is dispensed directly from the manufacturer's container and has a greater shelf life.

The UV cure machine required for the new acrylic material was obtained in the early to mid-1990s. The early version of the process was a belt-driven machine that cured one garnet at a time in 60 seconds. The process was later optimized in the early 2000s when a curing chamber was introduced that cures 10 garnets at a time in 60 seconds. Thus, touch labor as well as cycle-time were reduced.

2. Automated Sylgard Machine

Sylgard is a dielectric potting material that gets pumped into the core of the phase shifter (Figure 19). It displaces all air between the garnet core and the latch wire—providing an adhesive-like filler to keep out moisture and keep the garnet from vibrating and affecting phase-shifter performance.

In this process, an operator spends 3 hours a day mixing a two-part material which then has to be loaded into the pumping machine. This machine then pumps it into the phase-shifter housing. The mixed material has a one-hour shelf life; therefore, it must be used almost immediately. Since the material is manually mixed, usually one-third of it ends up waste.

In 2002, a process improvement introduced automation to the mixing process. A machine mixes the two parts on-demand, resulting in no waste and no shelf life. Additionally, the material is fresher and more consistent. The new process eliminated the 3-hour mixing operation and cut the dispensing effort by 50%. Before, an operator had to prep the pumping machine with the potting material; now, the machine mixes and pumps it directly into the phase shifter.

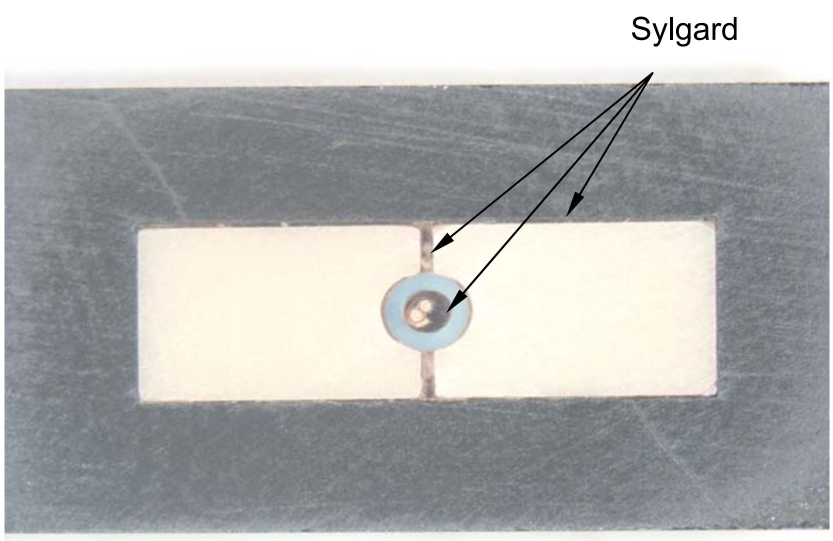

Figure 19. Cross-section of a Ferrite Core
(Source: Used for Permission from Lockheed Martin, 2006)

3. Robotics

Phase shifter assembly operations are difficult and labor intensive in high volumes (such as the 18,000 units required per ship-set). The fragile garnet interior component can be easily scratched or chipped, resulting in scrapping of the assembly. The phase shifter requires repeatable assembly to comply with strict specifications which ensure microwave performance characteristics. LMCO-Moorestown automated this process with robotics, thus significantly reducing touch labor.

The automation involves three work-cells consisting of Seiko D-TRAN robots which use programmable logic to simultaneously perform multiple and complex tasks. The first work-cell is used to pick and place 0.045-inch eyelets and ground contact springs to the phase-shifter housing. The assembly then goes to the second work-cell, where four rivets are placed onto the housing. The work-cell then spreads the tubular housing just below its elastic limit and inserts the fragile garnet assembly into the housing to within +0.002-inch in all directions. The housing is then closed while the robot holds the garnet assembly. The third work-cell automatically feeds a sub-miniature, A-sized coaxial connector, bends the microwave-sensitive probe precisely five degrees, and attaches the connector to the assembly using a patented Room Temperature Vulcanizing Silicon Encapsulate wetting method. The connector is placed over four rivets, and finally riveted into place to ensure no microwave leakage.

The automation of the phase-shifter assembly has had many advantages. Two shift operations are now performed during a single shift with one operator for each of these operations. The automation is reliable enough to free these operators to perform quality checks and chart statistical process control (SPC) data while the automated assembly operation is performed. This has resulted in an over 60% reduction in touch labor (Lockheed Martin, 2006). Additionally, the manual process variations and damage due to manual assembly are essentially eliminated.

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IV. OTHER PROCESS IMPROVEMENTS AFFECTING PRODUCTION

A. CONSOLODATED PURCHASING

In the past, each individual business unit of LMCO-Moorestown maintained and operated a complete and independent purchasing department. Few common practices spanned across these units, resulting in inconsistent sourcing and quality practices. Opportunities for increased buying efficiencies and overall cost effectiveness were often lost. Multiple organizations increased the number of suppliers as well as variation in the products. Lockheed Martin resolved this situation by consolidating the business units into three purchasing organizations, one of which is the Material Acquisition Center Mid-Atlantic Region (MAC-MAR).

MAC-MAR provides full-service sourcing for Lockheed Martin and some non-Lockheed Martin companies. The sourcing services include direct major subcontracting and indirect buying, supplier management, technology engineering, receiving, supplier quality assurance, inspection, freight management and cost estimating. The role of MAC-MAR goes beyond basic research; it also includes new development through production, and lifetime support after the product reaches the market. In addition, MAC-MAR actively participates in the shared corporate goals of Lockheed Martin such as the Six Sigma Program. Consolidation is also making it possible to do more within the Lockheed Martin acquisition community, such as technology road-mapping, instigating a global supplier base and systems integration.

Additional services and buying centers have been developed over time to include material cost estimating, field quality, freight-in, assessments, and subcontract agents. Commodity, indirect, and IT buying centers have also merged, in which MAC-MAR implemented an automated buying process. A consolidated purchasing approach provides tremendous leverage with suppliers while greatly reducing the cost of doing business. MAC-MAR improved total manpower productivity by 26.4% in its first 4 years, improved material quality by 128%, obtained the highest buyer productivity in LMCO, and reduced overall procurement costs by 32% (Office of Naval Research, 2001,

August). The administrative surcharge alone on acquisition services dropped from 10% in the early 1990s to 5% in 2000.

B. SUPPLIER PROCESS SURVEILLANCE

Previously, LMCO-Moorestown used traditional supplier product acceptance methods which relied on costly inspections upon receipt or at the supplier's location. Despite large numbers of dedicated inspection personnel, the company could not fully protect its assembly operations from process-related product anomalies. In 1999, MAC-MAR implemented Supplier Process Surveillance (SPS) which shifted the emphasis of quality from inspections to process controls (Office of Naval Research, 2001, August).

Supplier eligibility for the program is an active status with open purchase orders, sufficient parts quantities, and work in processes (WIPs). The first step of SPS is the creation of a Technical Data Package (TDP), which is a team effort by the technical specialist, technical engineer, and supplier. The TDP is used to baseline the supplier and takes about two months to complete. As a minimum, the package contains a process map, a surveillance plan, critical process identification, process indicator points (if applicable), and a surveillance schedule (which is a table of process checklists). Minimum requirements are determined by supplier category (e.g., manufacturer and distributor, manufacturer only, distributor only, and manufacturer of custom parts). Reviews are predetermined by the TDP team.

The technical specialist performs the checklists according to schedule. Review results are then forwarded to the technical engineer and maintained in the Supplier Quality System. If anomalies are found, corrective action is requested, and the supplier's quality rating is affected. The technical specialist communicates with various parties and visits the suppliers as necessary. After a three-month period, suppliers with good quality ratings may be evaluated for MAC-MAR's Dock-to-stock Program. Once approved, this qualification eliminates incoming inspections and shifts the burden to supplier process controls. Evaluation criteria include quality rating, corrective action status, trend analysis, critical process assessment, and an approved quality system. A Risk Review Board meeting is held to review supplier nominations. The Board consists of a Defense Contractor Management Agency representative, a quality-management supplier, a

technical engineer, and an SPS administrator. During these meetings, the Board can vote suppliers into a Dock-to-stock status.

SPS promotes predictable quality performance and efficient supplier oversight, thereby developing supplier process improvement and securing a high performance supplier base. Currently, over 250 suppliers are in the program (Lockheed Martin, 2006).

C. EIGHT-STEP PROCESS IMPROVEMENT PROGRAM

In the past, Lockheed Martin used traditional approaches (e.g., production readiness reviews, qualifications prior to production, etc.) for supplier quality management and development. During production, a reactive system monitored the supplier's quality performance and implemented corrective measures after trends were identified. Although somewhat effective, the company did not study the processes in detail nor optimize the opportunities for making improvements. Readiness reviews often lacked the thoroughness required to study in-depth process flows and preparedness for new/revised products introduced into the system. Reactive systems required fixes after significant damage had already been done—typically impacting product cost, quality, and delivery at a much higher level than if adverse conditions were corrected early in the production cycle. Seeing an opportunity for continuous improvement, MAC-MAR implemented the Eight-step Process improvement Program in 1998.

The Eight-step Process Improvement Program follows a detailed process flow that focuses on critical suppliers, materials, and processes; uses analytical tools to identify supplier trends; identifies critical manufacturing and/or part processes; and employs process surveillance to monitor risk areas. With the help of input by the business units, key suppliers are selected for review under the program. MAC-MAR assigns a lead engineer to facilitate a team of three to six people for each supplier, which then sets the eight-step process into motion. Team composition is personnel from other business units who have expertise in the products/processes related to the product to be delivered. The team uses various purchasing and performance databases to develop Pareto Analysis charts for review, and has access to the supplier to document, review, and analyze process flows. From these analyses and reviews, the team develops supplier action plans and requirements. The supplier makes the prescribed changes, and the team monitors the

performance. The combined progress of all the suppliers selected for the program is then charted to reveal the total impact of the Eight-step Process Improvement Program.

By 2001, 96% of the 59 key suppliers showed performance improvement, all impacting various degrees of quality, cost, and delivery of their products to Lockheed Martin (Office of Naval Research, 2001, August). The Eight-step Process Improvement Program is part of a powerful suite of tools and techniques employed by MAC-MAR to improve supplier performance.

D. LEAN AND SIX SIGMA

Six Sigma deployment and Lean integration has been an evolutionary process at LMCO-Moorestown. The company utilized a manufacturing process focus up through 1998, a design focus in 1999, and a business processes focus in the early 2000s (Office of Naval Research, 2003, April). The Quality, Ethics and Mission Success Organization developed the strategy, implemented the plan, and coordinated the driving change across the business. Today, Lean and Six Sigma is a structured process improvement methodology that significantly increases the involvement and effectiveness of employees in improving the systems they use to perform their work.

LMCO identified several key roles in pulling the Lean and Six Sigma methodology together, and it starts from the top. Figure 20 shows the overview of the process. A Senior Leadership Team (SLT) of top executives provides visible support through programs and resources to drive overall change throughout the organization. Functional organizations select Management Points of Contact to be the focal point of Lean and Six Sigma (e.g., project measurements, performance, results) in their areas. These individuals manage and focus resources, concurrent with identifying key project opportunities. The company also uses Master Black Belts (MBBs), full-time employees who have significant experience in Six Sigma and Lean methodology, in addition to changing management leadership. MBBs implement program strategy, lead projects, facilitate improvement events and provide training and mentoring for over 500 Black- and Green-belt employees trained in the Lean and Six Sigma philosophy. The key focus areas are: Transactional Lean and Six Sigma (which exposes sources of errors, rework, and non-value added steps), manufacturing Lean and Six Sigma (that prioritizes and

eliminates the most costly defects), and design for Six Sigma (that validates the availability of capability to meet customers' needs).

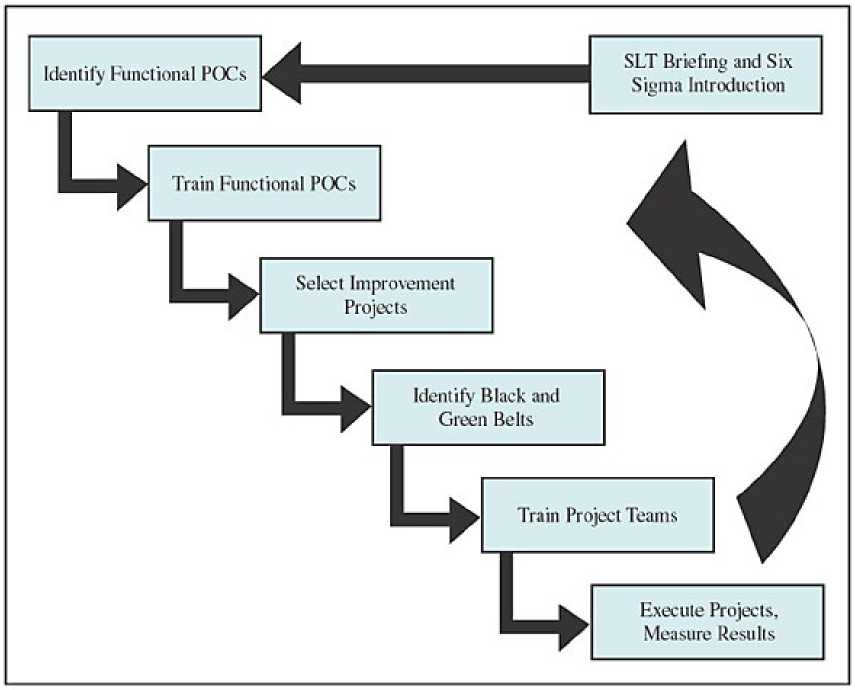

Figure 20. Process Overview
(Source: From Lockheed Martin, 2006)

Training courses are integrated into the Lean and Six Sigma approach, including Leadership Awareness, Black-belt Training, and Classical and Design for Six Sigma Green-belt Training. Monitoring and communicating performance are accomplished through project performance metrics, engaging the Financial Department upfront and through monthly project performance reviews. Other elements are communication and recognition. Communication vehicles include pamphlets, business reviews, newsletters, roundtables, and intranet web sites. Recognition and rewards include plaques, certificates, monetary awards, and giveaway items (e.g., mugs, jackets, shirts).

The return on investment of Lean and Six Sigma techniques is directly proportional to the commitment of business leadership. These techniques aid LMCO in providing effective tools to actively identify waste (i.e., defects and labor hours) and remove it from work processes. After waste is removed, techniques for sustaining improved performance are implemented.

E. PRODUCTIVITY IMPROVEMENT PROJECTS

In the early 1990s, LMCO defined a need to continuously improve its existing processes. Typically, these efforts were undertaken as a reactive approach to resolve production or quality issues. Increasing competitive demands and tightening shop budgets drove the need for a more structured approach. In 1998, the company developed goals for a refined and revitalized approach with a focus on proactive-driven improvements and cost reductions.

The Productivity Improvement Projects include renewed planning, improved reporting structure, and better capture of improvements versus baseline. The approach engages the company's strong experience base, with the Technical Support Team and Operations Management initiating and facilitating brainstorming sessions in selected Micro Businesses. The initial step involved prioritizing the Micro Businesses and systematically working through the list using multi-functional teams to focus on non-value added operations, rework, and scrap. The company also developed a process flow to facilitate the new approach (Figure 21), and a comprehensive database to support the entire operation from initiation to benefits tracking. These Productivity Improvement Projects take advantage of tools and concepts offered by Lean and Six Sigma.

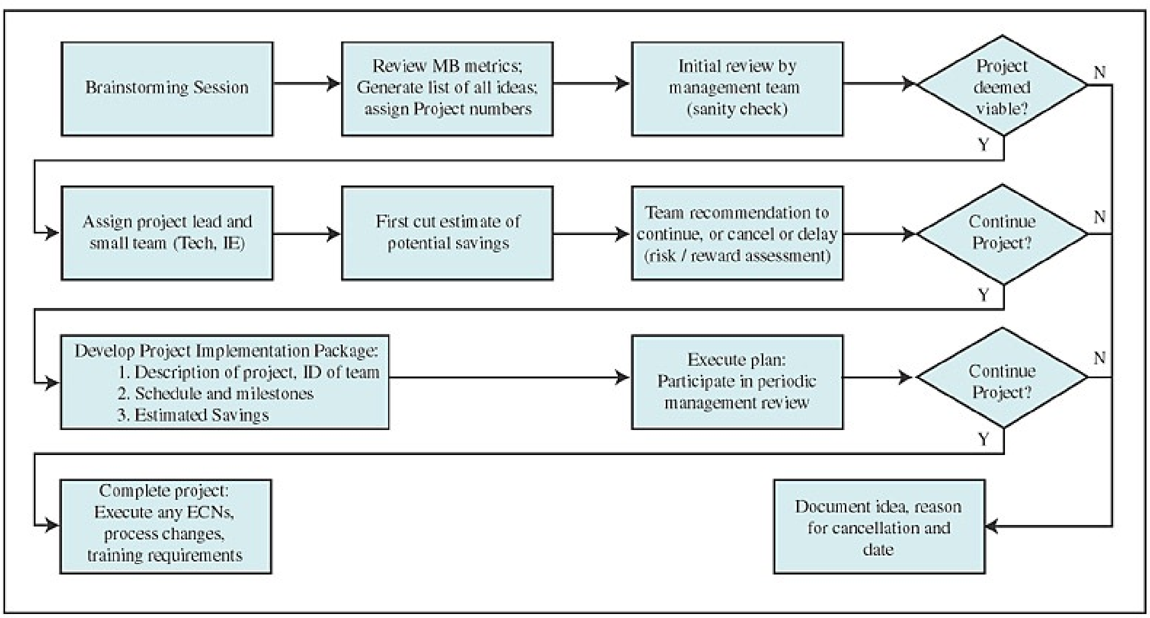

Figure 21. Process Flow
(Source: From Lockheed Martin, 2006)

Since 1998, more than 100 project ideas have been captured by LMCO. Some of Lockheed Martin's most significant projects include Tin/Lead Plating Elimination on Phase-shifter Connectors, Elimination of Epoxy Staking on Power Divider Assembly Connectors and Development of Push-on Combiner Test Connectors.

F. EMPLOYEE SUGGESTION PROGRAM

In 1991, a formal employee suggestion process was implemented as part of a major effort to help reduce costs and improve products, safety, quality, facilities, operations, and sales. This process was the typical paper-based system suggestion box that required manual handling for collecting, evaluating, and tracking employee suggestions. Looking for a new approach, LMCO implemented a web-based Employee Suggestion Program in January 2001.

The Employee Suggestion Program features a Suggestion Tracking System that operates as a comprehensive tool for inputting, storing, evaluating, and communicating suggestions throughout the organization. Suggestors can submit their ideas on-line as individuals, co-suggestors, or in teams. The Suggestion Tracking System facilitates ease in submitting ideas via a fill-in-the-blank electronic format. The system automatically generates e-mail to notify the various the cog departments. The goal of the Employee Suggestion Program is to answer each suggestion quickly, fairly, and accurately. Once a suggestion is initially evaluated and selected, it goes to a Suggestion Review Board comprised of cross-functional members—including management and union representatives. Every suggestion receives feedback of disposition and an explanation of the evaluation decision. Successfully implemented ideas can earn an award of 25% of the first-year savings for a team effort or 15% for an individual effort.

The Employee Suggestion Program's comprehensive tracking system takes advantage of the company's intranet to ensure the accuracy of the data without limiting the users. Figure 22 represents cumulative program savings for 1992-2005.

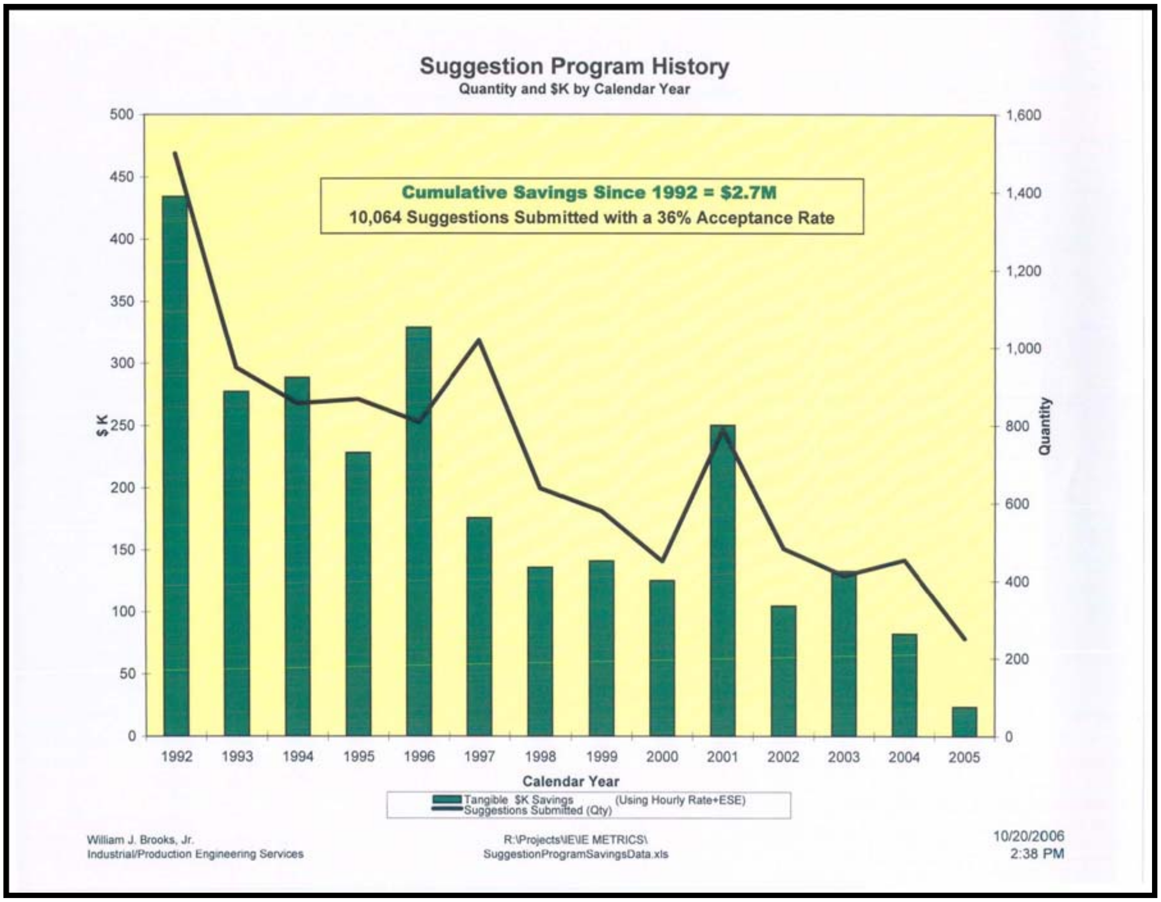

Figure 22. Employee Suggestion Program Cumulative Savings 1992-2005
(Source: Used with Permission from Lockheed Martin, 2006)

G. ENGINEERING CHANGE NOTICE

In the mid 1990s, LMCO-Moorestown converted its engineering change notice (ECN) process from a manual, labor-intensive, paper process to an automated, computer-based process. These changes allowed the company to better track the flow of an ECN and reduce its approval cycle. In the late 1990s, Lockheed Martin further refined this process by creating the Automated ECN/Problem Sheet System, an electronic workflow tool for creating, reviewing, and tracking engineering changes and manufacturing issues in the design and manufacturing environment.

ECNs are formal mechanisms for revising released engineering drawings. Problem sheets are formal mechanisms for documenting issues with engineering or process documentation. Lockheed Martin wanted to tie together the databases of these related, but separate, mechanisms. The goal was to replace the paper process across

various organizations with a single electronic process and to streamline the review and approval process. As a result, the company developed a common tool for creating documentation that still met the varying needs of its numerous users.

The Automated ECN/Problem Sheet System provides Lockheed Martin with an automated tool for creating, processing, and monitoring ECNs and problem sheets in the program management office, engineering, manufacturing, and sourcing departments. Standard and custom review screens give employees the ability to develop meaningful metrics of their processes. In 2005, more than 2,154 documents were processed under this system. The company also significantly reduced its total cycle-time (problem sheet investigation, analysis, ECN generation, and approval).

1. Engineering Change Notice Reduction

To improve its overall design process, Lockheed Martin needed a way to provide better visibility into the causes of Engineering Change Notices (ECNs). In addition, no method existed to prevent ECNs from recurring. To address these issues, the company implemented the ECN Review Board (ERB).

The ERB is comprised of Configuration MGT, Quality Assurance, MFG Eng, Producibility, and Operations Material Release. Meetings are held three times per week, and typically two to three additional individuals at random are invited to observe the process. At these meetings, the Board evaluates and categorizes all digital hardware ECNs, performs root-cause analysis on preventable ECNs, and identifies and incorporates process/tool/training corrective actions.

Engineers originating an ECN present the root cause and corrective action to the ERB. The Board can either approve or disapprove the action. If the Board disagrees with the recommendation, the engineer is given an opportunity to defend the proposed corrective action. The Board review is repeated until all parties agree on the suggested corrective action. At that time, the ERB assigns individuals to map the processes and to determine the costs associated with implementing the corrective action. At the next meeting, the responsible individuals present their reports to the Board which, in turn, adopts a corrective action. To prevent ECNs from recurring, a database tracking process is used.

Additional benefits include improved design practices and tools, and a reduction in ECNs, rework, and cycle-time. Since implementing the ERB, Lockheed Martin realized over one million dollars in cost-avoidance and savings.

V. AEGIS WEAPON SYSTEM CONTRACTS

A. INRODUCTION

This chapter identifies contracting influences and forces that may have had both direct and indirect influence over the AEGIS phase-shifter production improvements and R-TOC. These influences may have driven performance by LMCO, which in turn yielded process improvements, reductions in cost to the government, and increased phase-shifter reliability and producibility.

This chapter is by no means an exhaustive or all-inclusive study of the contracting arrangements for phase-shifter production or the correlation of contracting influences and specific results. It will describe the AEGIS weapon system contracts and the relation to phase-shifter production. The intent is to show any correlation between the appropriate use of contracting processes and the superior performance by LMCO that led to successful program outcomes.

B. CONTRACTS

The AEGIS Weapon System (AWS) contracts are production contracts that cover thousands of parts required to build the SPY radar systems, i.e., auxiliary equipment, support and test equipment, and equipment spares. The phase shifter, like all the other items, is a piece-part produced under the terms of the LMCO AWS production contract; therefore, phase-shifter specific incentives data was not readily available and would have required extensive collection efforts and complex analysis beyond the scope of this project. Since LMCO was only able to produce limited production contract data, only general correlations and conclusions may be drawn regarding direct effects on phase-shifter cost reductions.

1. Contract Type

All production contracts for the AWS that were identified and studied have been Fixed-price Incentive (FPI) contracts. This fact is aligned with the criteria for use described in Chapter one. The AWS is a mature system consisting of proven technologies. There is a decreased amount of risk to LMCO due to the history of work to produce and manufacture this system. This contract type allows LMCO to perform

contract requirements with an acceptable amount of risk and incentive, contrary to formal incentives discussed in the next paragraph, to increase profits by lowering costs and improving processes. This feature is inherent to the fixed-price arrangement because every dollar LMCO saves in costs is a dollar transformed into profit.

2. Incentive Structure

The incentive structure is a formula based incentive that includes a 50/50 cost and savings sharing ratio between the Government and LMCO. The contract requirements lend themselves to this incentive arrangement due to the ability to measure performance objectively. This requirement would not require the utility or flexibility of an award fee arrangement due to the low variation inherent in a high-volume production or manufacturing operation of a developed technology. The costs of a burdensome administrative and contract management effort would most likely outweigh the potential benefit derived from any increases in superior performance which may be produced by the award-fee incentive.

3. Contract Type and Incentive Results

By all accounts, the FPIF arrangement has had a significant influence on LMCO performance. This study has highlighted many of these reductions in cost and increases in product quality in previous chapters. LMCO sources have made direct reference to the sharing aspect of the FPIF contract as a motivating factor in contractor performance. One employee remarked, “The 50/50 share line on the contract pushes us to constantly search to find new ways to improve processes, decrease costs, and improve the product.”

While our research does not provide empirical data to prove significant correlation between the program successes and the contracting type or incentive influences, it does provide a framework and basis from which to draw conclusions about the potential for these practices to produce such results. The next section certainly illustrates the need for similar and more detailed research. The combination of the right contract type with an appropriate incentive structure work in concert to create a program landscape that has appropriate levels of risk for the Government and contractor and includes ample opportunity for mutual benefit. Such a balanced relationship leads to superior contract performance by the contractor.

C. PROGRAM INVESTMENTS AND SAVINGS

Contract incentives are not the only methods by which to increase program success or reduce costs. Contract specific investments are another way to create savings and inject improvements. Changes to the program, processes, or product through formal contract modifications and obligation of additional funding can result in significant savings from improved processes, reductions in cycle-time and lower production or manufacturing costs. LMCO has produced savings for the Government through a number of affordability initiatives on AWS contracts (Lockheed Martin, 2006).

Although no specific phase-shifter affordability investments could be identified, below are two examples of affordability investments made on AWS contracts that resulted in savings:

- The flexible phased-stable cables in the array columns were replaced with semi-rigid copper-outer-conductor cables ("Hardlines") of equivalent electrical length. This change is primarily to realize a cost savings, although marginal performance improvements are also realized.
    - Government Non-recurring Engineering (NRE) investment of $1,602,000.
    - Savings realized per hull of $2,141,000.
    - Cut-in hull of DDG-83.

- Phase-shifter driver DMS resolution redesign using Commercial-off-the-shelf (COTS) parts.
    - Government NRE cost of $3,600,000.
    - Savings per hull of $2,350,000.
    - Cut-in hull of DDG-111.

Reviewing these investments and understanding the magnitude of the net benefit makes it apparent that they are a worthy effort and can save the Government a great number of taxpayer dollars. Additionally, contractors would be encouraged and motivated to find opportunities for and make such investments on their own when

appropriate and sufficient contract incentives are utilized in the arrangement. A share in some of the total savings realized by a few of these investments demonstrates the potential shared savings or additional profit or fee that a formula based, sharing ration incentive contract could catalyze.

VI. SUMMARY AND CONCLUSION

In summary, the goal of this research was to provide a case study that captured the production and design processes and program management solutions used to reduce total ownership costs of AEGIS Radar Phase Shifters.

The phase shifter was an AEGIS Weapon System major acquisition cost-driver that was reduced to a medium-priced component through design and redesign, various process improvement projects, and other programs that improved phase-shifter production either directly or indirectly.

Phase shifters were initially designed for LMCO-Moorestown (then RCA) for approximately $2000 per unit in 1974; since then, LMCO has embarked on an aggressive campaign to productize the phase shifter. The resultant version (SPY-1A) brought down the acquisition cost of one ship set by $133 million (2006 dollars)—the first giant leap towards R-TOC of AEGIS Radar Phase Shifters. Shortly thereafter, the Navy sought to improve phase-shifter performance to reduce sidelobe levels. This was the next big challenge for LMCO because not only did the Navy want to improve performance, but it had incentivized LMCO to improve performance while concurrently keeping down the APUC. The result was SPY-1B: a radar system that incorporated significant advances over the SPY-1A radar, with improved detection capabilities as well as lower sidelobes. LMCO was able to increase phase-shifter performance by leaps and bounds for the next generation of radars, yet do it without increasing the APUC.

Throughout the 1980s and ‘90s, there have been many Navy FPIF contract incentives; consequently, there have been many LMCO process improvement initiatives to improve process yield and reduce touch labor. Through various defect- and scrap-reduction initiatives, LMCO improved defect yield from approximately 80% in the 1970s to 99.5% in 2006. It brought down touch labor by 40% between 1990 and 2006 through the implementation of robotics and other automation processes. The culmination of these process improvements have brought the APUC of a phase shifter from $200 in 1984 down to $80 in 2006—reducing the APUC another $4.47 million (or 76%) in 2006

dollars per ship set—thus, reducing costs of future acquisitions of AEGIS Weapons Systems.

LMCO not only worked diligently to directly improve its phase-shifter production processes, but it looked for other programs and avenues through which to lower total ownership costs indirectly, i.e., consolidated purchasing, lean and six sigma, productivity improvement projects, etc. More specifically, the establishment of MAC-MAR improved manpower productivity by over 26% in its first four years and reduced overall procurement costs of the AEGIS program by 32%; additionally, the implementation of Lean and Six Sigma and the Employee Suggestion Program have further reduced costs, improved products, safety, quality, operations, etc.

In conclusion, as a system progresses from early concept through prototyping, into production, and finally reaches the sustainment phase, the opportunities to significantly reduce Total Ownership Cost diminish. This clearly indicates that R-TOC efforts are most effective early in the developmental cycle where changes are least expensive and easiest to implement. However, TOC reductions can be effective throughout the system's lifecycle. The balance between capabilities and affordability means that more warfighting assets are available to the warfighter. TOC stakeholders have a vested interest in influencing the system design and development to yield a suitable, effective, and affordable solution. The challenge is how to accomplish this goal.

This challenge becomes greater in today's restructured acquisition environment. A key to success of the Aegis TOC reduction efforts noted in this report was the single program management office for the entire weapons system throughout its life cycle. Prior to 2002, "cradle to grave" shipbuilding responsibility including research, development, acquisition, construction and lifecycle support resided in one program office under the Assistant Secretary of the Navy for Research, Development and Acquisition (ASN RDA). After 2002, as part of the realignment under ASN RDA, 5 new Program Executive Offices (PEOs) were created—Ships, Carriers, Submarines, Littoral and Mine Warfare, and Integrated Warfare Systems (IWS). This restructuring effectively terminated the unique management structure of Aegis which enabled major TOC reductions.. As a result, the individual Weapon Systems acquisitions for all ship classes

now fall under one umbrella, PEO-IWS, while PEO-SHIPS maintains most of the aforementioned shipbuilding responsibilities of surface combatants. PEO-SHIPS no longer has cradle to grave responsibility for the end use weapon system as a whole.

As one may envision, because of its size and complexity and long-term lifecycle requirements, separating program management (thus, ownership) of the major weapons acquisition function from shipbuilding may present significant challenges to major TOC reduction efforts for future ships. Since the majority of lifecycle sustainment costs are best addressed up front, and if PEO-IWS only overseas the construction and purchase of the new, individual, weapon systems before passing them to PEO-SHIPS, will there be sufficient focus to allow down-the-road lifecycle R-TOC efforts? Only time will tell and this subject is recommended for future research. As evident in this case study, past successes of R-TOC of AEGIS Radar Phase Shifters are a direct result of long-term Program Management and Stakeholder relationships from development and acquisition through integration and sustainment.

An acquisition strategy prevalent in Aegis which enabled R-TOC efforts was "strategic partnering." Strategic Partnering is a long-term, mutually beneficial business relationship containing specific elements unique to the relationship; it is an agreement detailing performance requirements and conditions, structures to promote successful interaction between parties, organizational alignment, clear measures of success, and a high level of mutual commitment. Long-term contracts and collaboration generally foster lower costs due to the greater incentive to make transactional-specific investments, the sharing of information and value engineering with the resulting enhanced learning curves. This AEGIS case clearly demonstrates a compelling and undeniable example of this. Although limitations on contract length and competition requirements in federal contracting are well-founded and justified, the acquisition community needs to consider the many benefits possible with contracting and long-term strategic partnerships.

One of the more intangible benefits of strategic partnering worth mentioning in this report is the longevity of both government and contractor employees in a program, and the benefits it lends to program success by way of capturing experience and corporate knowledge. For example, in the 1990s, LMCO-Moorestown established a twice-monthly

communications meeting to promote effective working relationships. Critical matters such as material management, forward pricing rates, interim/final billing rates, and cost-savings initiatives were resolved in a timely manner (Office of Naval Research, 1995, October). The meetings also fostered open communications that built trust and teamwork, resulting in increased efficiency and better utilization of resources. Today, LMCO-Moorestown uses Integrated Production Team's (IPTs) where issues and problems can be immediately resolved. This approach results in real-time customer feedback and reduces the chance for misunderstanding, thereby increasing customer satisfaction. These are prime examples of how government/contractor employee longevity contributes to the long-term success of a program (Greene, 2006).

LMCO's reduction of production costs, when combined with Navy FPIF contracts and long-term partnering, has been extremely successful in driving down phase shifter total ownership costs. The production and management processes used to achieve these results are important to understand in light of post-Cold War defense spending cuts and acquisition reform. This case study both validates these successes and identifies the underlying factors that catalyzed them, while highlighting the vital role that Lockheed Martin Maritime Systems & Sensors (MS2) at Moorestown played in reducing the acquisition costs of past and future AEGIS Weapon Systems.

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